

# Recent Progress in Baryogenesis

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**Abstract.** I give a synopsis, specifically aimed at nonexperts, of some of the recent developments in electroweak baryogenesis. The focus of the talk is on the present status of electroweak baryogenesis in supersymmetric models, since this is a plausible and realistic possibility that is currently being probed by experimental searches for the Higgs boson and the top squark. The question of whether it is viable to have a period of color-breaking during the electroweak phase transition is also discussed.

## BARYON ASYMMETRY OF THE UNIVERSE: REVIEW

The baryons within the observed universe appear to consist essentially only of matter and not antimatter. There are no regions of gamma ray emission which would correspond to the collision between a galaxy made of normal matter with one made from antimatter, for instance. Moreover, the theory of Big Bang nucleosynthesis gives predictions for the abundances of primordial helium (both  $^4\text{He}$  and  $^3\text{He}$ ), deuterium and lithium, if the ratio of baryons to photons in the universe is in the range

$$2 \lesssim \eta_{10} \lesssim 6; \quad \eta_{10} \equiv \frac{n_B}{n_\gamma} \times 10^{10}.$$

If we do live in a universe with equal quantities of matter and antimatter, then the two must somehow be separated on distance scales greater than the present Hubble length, that is, the size of the presently observable universe. The simplest assumption is that indeed the whole universe has the same preponderance of matter over antimatter. It is a deep mystery of cosmology why the abundance of baryons should be this peculiar number,  $10^{-10}$ , relative to the number of photons.

The mystery is intensified by the fact that the most natural initial condition of the universe, at the time of the big bang or shortly thereafter, *is* to have equal numbers of baryons and antibaryons,

$$n_B = n_{\bar{B}},$$

implying that the net baryon number of the universe was zero. There are several reasons for believing this.

1. Baryon ( $B$ ) and Lepton ( $L$ ) conservation are *accidental* symmetries of the Standard Model (SM): there is no good reason for them to be exact. For example, a dimension 9 operator consisting of 6 right-handed quark fields in a color singlet state,

$$\Lambda^{-5}(u d d)^2$$

is allowed by the gauge symmetries, and would lead to neutron-antineutron oscillations at some rate suppressed by the large mass scale  $\Lambda$ . At sufficiently high temperatures  $T \sim \Lambda$  in the early universe, however, the effects of such a baryon number violating operator would be unsuppressed.

2. *Sphalerons*, present within the SM itself, violate  $B$  and  $L$  (but not  $B - L$ ). These are the lowest energy field configurations with Chern-Simons number  $1/2$ , intermediate between neighboring  $N$ -vacua of the  $SU(2)$  electroweak gauge theory. (A sphaleron can be thought of as the  $t = 0$  slice of an instanton, such as occur in QCD. In QCD it is chirality, rather than  $B + L$ , which is anomalously violated.) Local transitions which go from one  $N$ -vacuum to a neighboring one must pass through a sphaleron-like configuration. Because of the triangle anomaly in the baryon and lepton currents, each such transition is accompanied by 9 quarks and 3 leptons. At zero temperature, the energy barrier between the  $N$ -vacua, which is the sphaleron energy, is near 10 TeV, and the tunneling rate for the anomalous transition is so slow as to be entirely irrelevant. But at temperatures above that of the electroweak phase transition,  $\sim 100$  GeV, this energy barrier disappears, and sphaleron transitions are fast compared to the Hubble expansion rate in the early universe.
3. Grand Unified Theories also violate  $B$  and  $L$  through heavy gauge boson ( $X$ ) vertices of the form  $Xqe$  or  $X\bar{q}q$ . The presence of both such interactions prevents one from assigning a conserved  $B$  or  $L$  number to the  $X$  boson.

Because of these sources of  $B$  violation, we would expect that any initial  $B$  or  $L$  asymmetry that might have been present initially would be quickly wiped out, giving

$$B = L = 0$$

as the effective initial condition at the high temperatures of the very early universe. Therefore something must have happened between now and then to produce the observed baryon asymmetry.

It was realized by Sakharov in 1967 that three things are needed to spontaneously generate the baryon asymmetry: baryon number violating interactions,  $CP$  (particle-antiparticle symmetry) violation, and loss of thermal equilibrium for the  $B$ -violating interactions. The first two features are present in the SM by virtue of sphalerons and the phase in the CKM matrix for the quarks. This source of  $CP$  violation is however too weakly coupled to the mechanism of baryon production to produce a large enough asymmetry. The third condition is unfulfilled in the SM

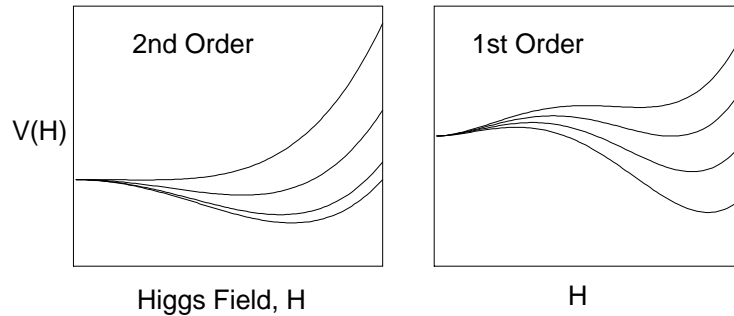
model: the transition between the symmetric and the broken phase of the electroweak theory is so continuous that it is not a phase transition at all. Sphaleron interactions, although they eventually drop out of thermal equilibrium, do so too gradually to allow the universe to go from a state of  $B = 0$  to one of nonzero  $B$ .

We therefore need new physics beyond the SM for baryogenesis. Many particle physicists believe that supersymmetry is the most natural direction in which to look for such new physics, and I will also take that point of view. Moreover, I will confine my remarks to electroweak baryogenesis, even though much interesting work on nonelectroweak baryogenesis scenarios has been done in the last year [1].

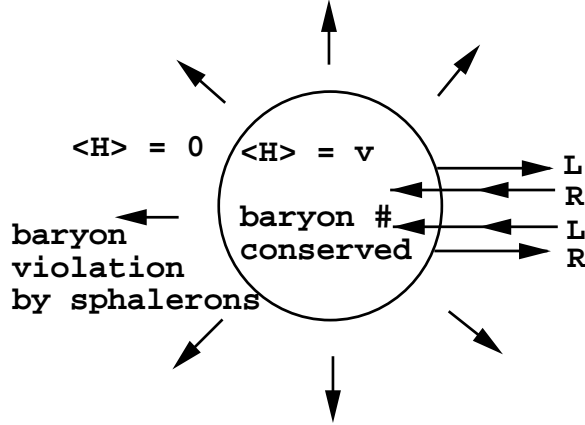
## ELECTROWEAK BARYOGENESIS IN THE MSSM

Electroweak baryogenesis within the minimal supersymmetric standard model (MSSM) has evolved far beyond the status of being just a rough, qualitative theory. Rather, it has been the subject of intense, highly quantitative scrutiny, thanks to the fact that it is so much in the realm of currently testable physics. The way it must work is rather well-defined. First, the electroweak phase transition must be first order, which requires the Higgs field potential to have a barrier between the symmetric phase minimum at  $H = 0$  and the true vacuum state with  $H \neq 0$ , as shown in figure 1. Under these conditions, the phase transition proceeds by the nucleation of spherical bubbles containing the new  $H \neq 0$  phase within. The bubbles quickly expand and fill the universe with the broken phase.

Between the initial nucleation and the completion of the phase transition, particles in the high- $T$  plasma are encountering the expanding bubble walls (figure 2). Most particles are massless outside the bubble and massive within, so the bubble wall behaves like a quantum mechanical potential which can scatter the particles. In general there is partial reflection and transmission of particles at the wall, with left-handed particles reflecting into right-handed ones, since spin is conserved, and vice versa.



**FIGURE 1.** Higgs potential near a second order (left) or a first order (right) phase transition, for a series of temperatures.



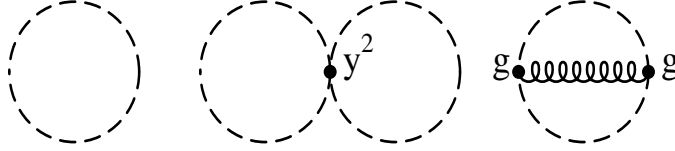
**FIGURE 2.** The expanding bubble wall during a first order electroweak phase transition.

It is in the reflection process that  $CP$  violation is important. If  $CP$  is violated on the wall, then particles and antiparticles can have unequal reflection probabilities. The same is true for left-handed and right-handed fermions. Thus an excess of left-handed quarks versus antiquarks can build up in front of the wall (compensated by an equal and opposite excess of right-handed quarks so that net baryon number is still zero at this point).

The asymmetry between  $q_l$  and  $\bar{q}_l$  increases the free energy of the plasma locally, and sphalerons try to minimize this energy by destroying the  $q_l$ - $\bar{q}_l$  asymmetry to some extent, redistributing it among the other species of quarks and leptons. This biases the sphalerons to preferentially create an excess of baryons or antibaryons, which resides in front of the wall for a time, but eventually falls inside the bubble and becomes the baryon asymmetry of the universe (BAU) that is observed today. However the BAU can survive inside the bubbles only if sphaleron interactions are essentially shut off. This is because the  $CP$  asymmetry is not operative inside the bubbles (since chirality is not a good quantum number in the broken phase) to insure that sphalerons act preferentially to make only baryons or antibaryons. If sphalerons are not turned off, they will erase whatever BAU is created.

The above idea is highly constrained. For example, it does not appear feasible to alter the basic mechanism by replacing bubbles with other field configurations such as cosmic strings, despite the fact that this possibility has been widely discussed in the literature. We have recently shown [2] that the cosmic string scenario, when scrutinized more carefully, underproduces the baryon asymmetry by 10 orders of magnitude. The reason is essentially that  $CP$  violation at the string walls is proportional to the string velocity squared,  $v^2$ , while the density of strings in the network scales like  $v^{-2}$ . It was previously assumed that the strength of  $CP$  violation and the string density could be independently varied.

However, the most important constraint on electroweak baryogenesis is the condition for making the sphaleron interactions slow enough to preserve the BAU, which turns out to be



**FIGURE 3.** Some of the virtual squark diagrams contributing to  $V(H)$ .

$$\langle H \rangle \geq T \quad (1)$$

inside the bubbles, where  $\langle H \rangle$  is the field value that minimizes the potential energy. Although impossible to achieve in the SM, it is possible in the MSSM, provided that the right-handed top squark and the lightest Higgs boson are sufficiently light. (A light left-handed stop is disfavored by precision electroweak considerations, namely the rho or  $T$  parameter.) The significance of the top squark is its large Yukawa coupling  $y$  to the Higgs field, whose potential  $V(H)$  controls the phase transition. Top squark loops such as those shown in figure 3 contribute cubic terms of the form  $-y^3 T H^3$  to  $V(H)$ , which make it possible to fulfill eq. (1). This can be understood in terms of the standard expression for the free energy of a relativistic gas of bosons, represented by the one-loop diagram in figure 3, which when expanded in powers of the boson mass over temperature contains a term proportional to  $m^3 T$ . Since the mass of the squark depends on the Higgs field, this increases the magnitude of the negative  $H^3$  term in  $V(H)$ .

We have studied the EWPT in the MSSM using the two-loop effective potential, and varying the parameters of the MSSM randomly over many thousands of values to search for those which give a strong enough phase transition [3]. Our results are in reasonable agreement with several similar studies [4]-[9], in predicting the mass ranges for the Higgs boson and the stop to be

$$\begin{aligned} 85 \text{ GeV} < m_h < 107 - 116 \text{ GeV} ; \\ 120 \text{ GeV} < m_{\tilde{t}_R} < 172 \text{ GeV} . \end{aligned} \quad (2)$$

The lower bound on  $m_h$  is from the latest  $L3$  (LEP) experimental limit [10] (the MSSM version of this bound is weaker than in the SM), and the upper bound is a function of the heavy stop mass, because its radiative corrections to  $m_h$  grow logarithmically with  $m_{\tilde{t}}$ .

One might hope that the chances of observing such a light stop at the Tevatron would be good. But experimental limits on  $m_{\tilde{t}_R}$  often depend on other unknown MSSM parameters that determine which production channels are open to  $\tilde{t}_R$ . For example, the greatest sensitivity to squarks is when they are produced along with gluinos, but if the gluino mass exceeds  $\sim 300$  GeV then light squarks are difficult to identify. [11] Similarly, the baryon production mechanism at the bubble wall prefers values of the  $\mu$  parameter and Wino mass  $m_2$  in the range  $|\mu| \sim m_2 \sim 100$  GeV, which would inspire hopes for the imminent discovery of the chargino [12,13]. This range of values is in fact excluded by chargino searches for  $\mu > 0$ , but not for  $\mu < 0$ .

For these reasons, the most foolproof experimental test of electroweak baryogenesis is the search for the light Higgs boson. The remaining window (2) is rapidly being closed by the LEP2 run at CERN. It is a pity, though, that LEP2 will terminate with a limit of only  $m_h < 107$  GeV, leaving a small unexcluded window of Higgs mass values. However it is possible that a better theoretical determination of the Higgs mass, using the renormalization group, could help to close this window.

## COULD COLOR HAVE BEEN BRIEFLY BROKEN?

One of the interesting possibilities that has been suggested in connection with electroweak baryogenesis with a light stop is that the SU(3) gauge group of QCD was temporarily broken. In order to get a sufficiently light right-handed stop, its bare mass-squared parameter must have been *negative*, so that the field-dependent stop mass has the form

$$m_{\tilde{t}_r}^2 = -\tilde{m}_U^2 + y^2|H|^2 + \frac{g_s^2}{6}|\tilde{t}_R|^2$$

This makes the symmetric vacuum unstable toward condensation of the stop field in some random direction in color space. If  $-\tilde{m}_U^2$  is sufficiently negative, it can be energetically preferable to have a period of color breaking before the normal electroweak vacuum state takes over. In this case one would have the sequence

$$(H, \tilde{t}_R) = (0, 0) \xrightarrow{1} (0, v_{\tilde{t}}) \xrightarrow{2} (v_h, 0)$$

of phase transitions, which would change our view of cosmological history in a very interesting way. For example, the second transition tends to be very strong, which is favorable for baryogenesis. But there is an energy barrier impeding this second stage of the transition, due to a positive term in the potential

$$y^2|H|^2|\tilde{t}_R|^2$$

whose presence is mandated by supersymmetry. It could happen that the rate of tunneling from the color-broken to the electroweak phase is so small that it will never happen in the history of the universe. Guy Moore has made the following conjecture: if  $m_{\tilde{t}_r}$  is ever small enough for transition 1 to take place, then the universe gets stuck in the color broken phase and never completes transition 2. Although preliminary studies of this question have been done, it deserves a more careful treatment.

We have undertaken such a study, by constructing the full two-loop effective potential  $V(H, \tilde{t}_R)$  for the Higgs and stop fields, and computing the nucleation rate for the most likely bubbles interpolating between the color-broken and electroweak phases [14]. This involves finding the path in the  $(H, \tilde{t}_R)$  field space along which the bubble evolves, which gives the lowest bubble energy, hence the fastest rate

of transitions. The field equations with boundary conditions  $(0, v_i)$  and  $(v_h, 0)$  at the respective ends must be solved along this path. One needs a value of bubble energy over temperature smaller than  $E/T \cong 180$  to get a tunneling rate per unit volume,  $\sim T^4 e^{-E/T}$ , that is competitive with the Hubble rate per Hubble volume,  $\mathcal{H}^4$ . That is,  $E/T$  must be less than  $4 \ln(T/\mathcal{H})$ . However, we find that even when all MSSM parameters are adjusted to the values that are optimal for tunneling, the exponent  $E/T$  is too large by an order of magnitude. It therefore appears that one must go beyond the MSSM in order to make color-breaking a real possibility just before the electroweak phase transition.

## FOR THE FUTURE

Although the electroweak phase transition in the MSSM is now well understood, the details of how baryons are produced at the bubble wall are still controversial. This is a highly complex phenomenon involving quantum reflection or classical forces acting on the particles near the wall, while they are simultaneously being scattered by other particles in the plasma. It is likely that the Quantum Boltzmann Equation will be needed to put this part of the theory on a more rigorous footing.

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